

RAWS--THE SPACEBORNE RADAR WIND SOUNDER
ANNUAL PROGRESS REPORT--1991

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1.0 INTRODUCTION

This is a report of progress in the first year of the University of Kansas study of the concept of a Radar Wind Sounder (RAWS). We have made much progress in this study, but much more remains to be done. A completed dissertation on the subject by W. Xin [1] addresses the general concept and some of the most difficult technical challenges. It shows that the concept is feasible and presents methods for solving the more difficult problems.

Xin's dissertation uses only three simplified models for clouds and none for rain. We later conducted a more extensive study of cloud models and the resulting RAWS signal-to-noise ratio (SNR) for different conditions, although the report on this is still in progress. One encouraging conclusion is that ice clouds have high-enough radar cross-sections that a radar with a given power can measure winds by the Doppler shift from ice clouds with lower densities than we previously thought possible. An alternative interpretation would be that lower power could be used to get the winds in the ice-cloud regions, provided winds in some of the thin water clouds could be missed.

The goals of RAWS are to estimate the following three quantities:

- a. the echo power--to determine rain-rate and surface wind velocity;
- b. the mean Doppler frequency--to determine the wind velocity in hydrometers;
- c. the spread of the Doppler frequency--to determine the turbulent spread of wind velocity.

Work to date dealt with b., the wind measurement. However, this necessarily required treating both a. and c.

2.0 BASIC TECHNICAL PROBLEMS

The most difficult technical challenges in the RAWS design are:

1. Determination of Doppler centroid,
2. Provision of a suitable antenna scan, and
3. Obtaining adequate sensitivity for clouds.

2.1 Power and Sensitivity.

Xin calculated power requirements for the Doppler wind sensor for a few simple cloud examples. A radar such as this would be useful even if it only measured winds in rain, but its value would be much greater if winds in the interior of clouds could be measured. The power levels suitable for a rain radar would seldom if ever allow cloud measurements with adequate signal-to-noise ratio, so the clouds determine the requirement.

Use of large antennas and power in the few-kW range would allow wind measurement in most of the denser water clouds and in ice clouds with lower mass density. This power would be useful in most convective cloud systems. The peak-power level is comparable with that for the SIR-C, ERS-1, and EOS SARs. Antennas as large as 15-m diameter have been designed for use with frequencies up to Ku band. However, the RAWS antenna need not be this large.

The radar initially used for an example has an antenna 8 m in diameter, frequencies of 10 and 35 GHz, peak power of 3 kW and average power of 100 W, and 150-m slant-range resolution with a 20- μ s expanded pulse. For 35 GHz, adequate S/N is available for a mean drop radius slightly above 10 μ m. Increasing the peak power to 5 kW (500-W average), a value close to those used by forthcoming spaceborne SARs, gives adequate 35-GHz S/N for mean radii >8 μ m.

SNR is never adequate for clouds at 10 GHz, but the lower frequency is needed for cases when rain is present. Attenuation through the rain is so high at 35 GHz that one could not measure at levels near the surface.

2.2 Determination of Doppler Centroid.

The RAWS must measure the components of the velocity of the hydrometers along the lines joining the radar and the observed volume. If one wishes to measure the horizontal velocity to about 2 m/s, a radar beam entering the atmosphere at 30° from vertical must measure to within 1 m/s.

The spectrum of velocities resulting from turbulent motion will be offset from zero. The offset (center of spectrum) will be the sum of two components: the component of the mean wind vector in the direction of the radar and the component of the spacecraft velocity in the direction of the measured volume. The finite width of the radar beam, however, means that the velocity components to different parts of the beam differ even for a stationary target. Thus, the Doppler frequencies associated with the turbulent motion and the spread of the beam form a spectrum of considerable width. The RAWS must measure the centroid of this spectrum and remove the effect of spacecraft motion.

Accurate determination of the Doppler centroids for observed volumes will require comparison with the Doppler centroids for the surface echoes. Otherwise the small Doppler shifts due to wind would be lost in changes in the Doppler shifts due to spacecraft attitude changes. This occurs because the velocity component due to spacecraft motion at 30° ahead, for example, is of the order of 3700 m/s, whereas the wind-speed components to be measured are only a few m/s. An error of 0.1° in pointing would be equivalent to 11 m/s, an intolerable value. However, since both the surface echo and the rain/cloud echo are subject to the same shift due to pointing errors, the difference can be accurate. Hence, we must measure both surface and hydrometer Doppler shifts and use the difference in their centroids to estimate the wind velocity. At 30° the center frequency of a stationary surface echo varies from -250 kHz through zero to +250 kHz for a circular scan. Hence, such a radar needs programmed Doppler filters, so the center frequency of the spectrum due to the narrow beam can be kept within range for rapid tracking. Since orbital parameters are reasonably well known, this kind of program can easily be incorporated. Even so, the tracking problem is not trivial. For an antenna with 2-mr beamwidth pointed 30° ahead, the spectral width would be 307 m/s. Thus, if precision of ± 1 m/s is required, the RAWS must locate the center frequencies for the surface and rain spectra to within about 0.3% of their bandwidth or 0.027% of their absolute value. Xin studied this problem and came up with a preliminary plan to handle it. Further studies of the integration time are needed to achieve this measurement.

Ambiguity in Doppler-frequency measurement is a major problem in such a system. Presuming that one can remove the spacecraft-induced velocity by using a programmed local oscillator to beat this Doppler frequency to zero, one must still contend with the Doppler bandwidth caused by the motion of the particles to be measured. For a windspeed of 100 m/s, the maximum component along a 30° line of sight is 50 m/s. At 10 GHz this means Doppler frequencies of ± 3333 Hz must be measured. At 35 GHz, ± 11667 Hz must be measured. Even if the spacecraft pointing errors were perfectly removed, this means the Nyquist sampling rates would equal 6.67 kHz for 10 GHz and 23.33 kHz for 35 GHz. This rate is too high to avoid range ambiguities.

Xin showed that overcoming range ambiguities requires an interpulse period of 200 μ s, or PRF of 5 kHz. The Nyquist criterion for measuring the Doppler frequency F_D without ambiguity requires that $\text{PRF} > 6.67$ kHz at 10 GHz, so this criterion cannot quite be met. At 35 GHz the situation is worse, for the Nyquist frequency is 23.67 kHz.

The ambiguity problem is also important for ground-based weather radars and has been studied extensively. Xin studied various approaches used in the ground-based application, as well as some unique modifications, and showed the errors with different approaches under RAWS conditions. His basic conclusion is that a modified dual-pulse system will work best for RAWS, giving reasonable errors in wind estimates with SNR of 5 to 10 dB.

2.3 Antenna Scanning.

The antenna for RAWS must be large if cloud echoes are to be received. This poses problems in the scanning of a large antenna and in the timing required to assure adequate coverage and accuracy of measurement.

The initial plan is to use a large parabolic-reflector antenna with two feeds and 360° scan. For example, if an 8-m dish is used, the beamwidth at 35 GHz is only .06°, which means the along-scan beamwidth is only 463 m. The Doppler shift associated with 1 m/s at 35 GHz is 232 Hz, so the beam must dwell at least 4.3 ms to measure with this precision. A circle 600 km in diameter has circumference of 1885 km, so the time for a revolution must be at least $1885/0.463 \times 0.0043$ or 17.5 seconds. Realistically, it should be at least twice that. During this time the

spacecraft advances 131 km. This is a feasible scan rate, although it may pose significant inertial problems.

Xin proposes a form of step scanning to go with the circular scan. In this approach the antenna feeds would be small phased arrays so that the beam could be squinted slightly to remain on a given target volume while the antenna continues to rotate. At the end of such a dwell time, the feed would jump the beam ahead to the next volume. With this approach one has much more flexibility in choice of rotation rate for the scanning main reflector.

Step scanning would also be possible if an electronically scanned array were used. Two arrays would be needed, one scanning ahead of and one behind the spacecraft. Fortunately, full 180° coverage would not be needed for each array, since scans directly to the side or directly ahead would not permit multiple-direction looks at a given spot. Thus, scanning would need to be only about $\pm 70^\circ$, which is feasible but difficult for a single array. Step scanning has the advantage that the beam can dwell longer on selected spots that fit the output grid, while omitting areas that do not fit the grid. This results in improved precision of measurement.

Although we did not treat this approach so far in this project, the nearly complete dissertation of Mr. Duc Kieu treats it for a rain radar with a similar scan pattern. Kieu also considers the use of a scanned reflectarray. This approach is quite promising for his radar and seems a likely approach for RAWs as well.

The other part of the scan problem is to achieve the four looks at each point in a grid suitable for forecasting. We find that looking at exactly the same spot with each beam is not feasible over the entire swath with continuous antenna rotation. Hence, the measurements with the different beams and beam positions will be non-coincident, but in the same area. Use of such data depends on the assumption that the wind is steady over some reasonable area so that the components of the wind vector obtained at different spots within the area may be combined. Because of mesoscale variability of winds, this would increase the error of measurement. However, continuity of flow over large areas can be used to smooth this random fluctuation. This topic needs more study.

3.0 SUMMARY OF PROGRESS

Details on much of the progress during the initial year of this study reside in the Ph.D. dissertation of W. Xin. This document was complete in June, and represents the major contribution for this year's work. Here we only very briefly summarize highlights of the findings.

The Xin dissertation concentrated on an initial feasibility study and solution of the more difficult technical challenges for RAWs. For this reason, only three cloud models were used (with 0.1, 0.3, and 1.0 g/m³). He used no rain models and no combination rain-cloud models. Since completion of this part of the work, we have extensively studied the effect of different cloud models on results and on tradeoffs possible between power, antenna size, and system performance under different conditions. We prepared computer simulation programs and used them for many calculations. The results of these calculations will appear in a forthcoming technical report; here we present only samples.

We anticipate that, soon after these documents are published, we will extract portions of them for publication and presentation at technical meetings.

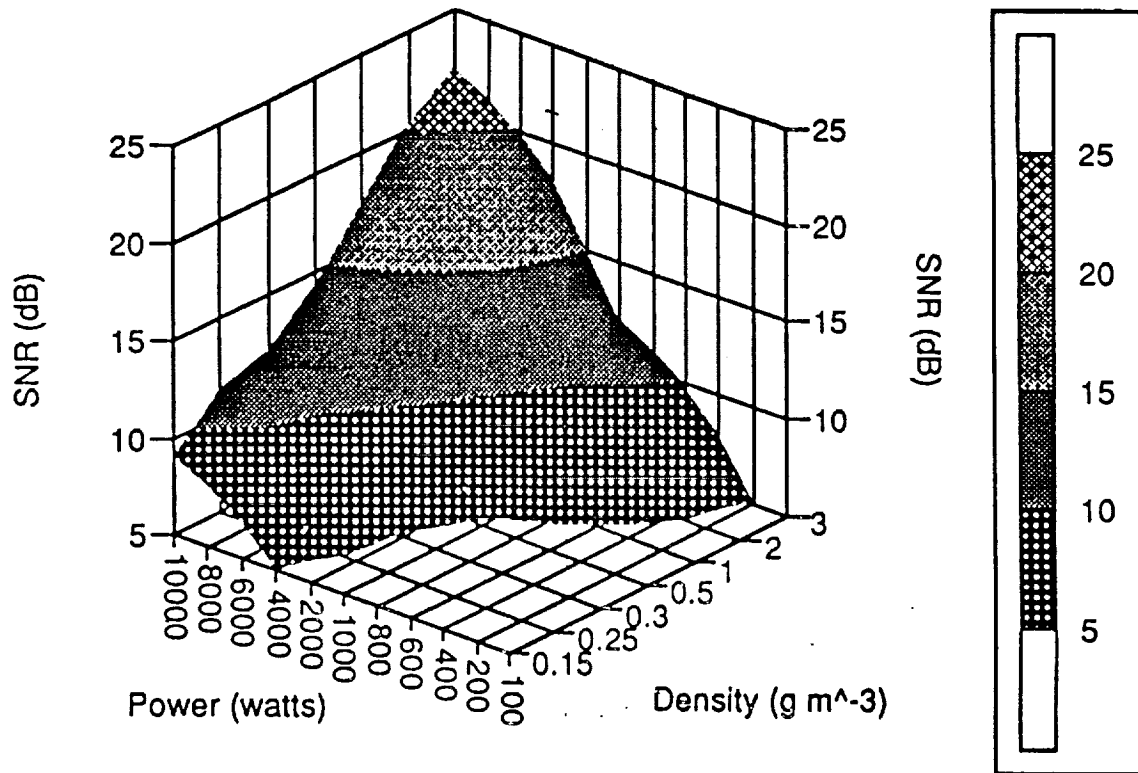
3.1 Literature Study.

Xin conducted an extensive literature survey on cloud models, Doppler measurement in the presence of ambiguities, frequency tracking, and other relevant topics. He paid particular attention to models for the drop-size distributions. The resulting bibliography appears in the dissertation. Since its completion, we have searched the literature further, particularly with regard to cloud and rain models. This additional material will appear in the technical report on trade-off studies.

3.2 Power and Sensitivity Study.

Our initial calculations, based on the reference system postulated by Xin, used only a few rain and cloud models. The reference system uses frequencies of 10 GHz for heavy rain and 35 GHz for light rain and clouds. It has an 8-m-diameter antenna (gain 68 dB at 35 GHz and 57 dB at 10 GHz). The beamwidths are 1.2 and 4.7 mr, respectively. The power is 3-kW peak with 20:1 range compression to allow an equivalent peak power of 60 kW. Slant-range resolution is 150

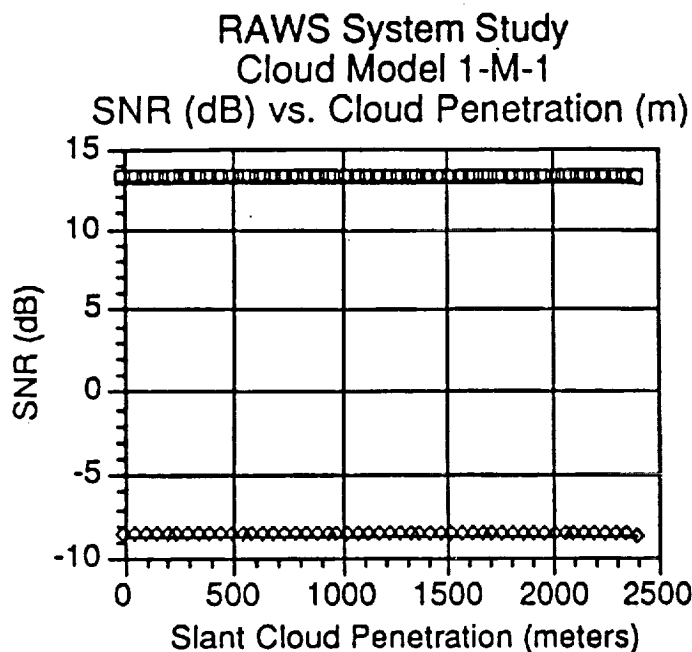
RAWS System Study
 SNR (dB) as a function of Power (watts)
 and Water Density (g m^{-3})



Water clouds @ 1500-2000 meter elevation
 $f = 35 \text{ GHz}$
 mode radius = 10 micrometers
 shape parameter $C1 = 6.0$
 shape parameter $C2 = 0.5$

Figure 1. Three-dimensional tradeoff plot between SNR, cloud density, and transmitter peak power for 800 km orbit. Fair weather cumulus with with 10 μm mode drop radius. Cutoff at 5 dB SNR is level for good precision of measurement.

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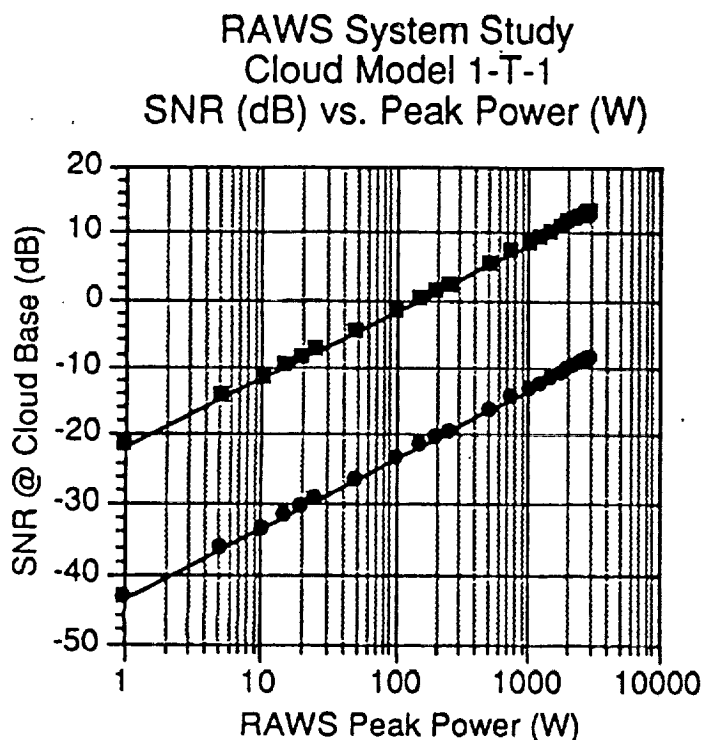


—□— SNR (dB) @ 35 GHz
—◇— SNR (dB) @ 10 GHz

Cirrostratus, Mid-Lat
Elevation: 5000-7000 m
Density: 0.10 g m⁻³
Principal Component: Ice

Default System Parameters

Figure 2. RAWS SNR vs cloud penetration for 800 km orbit. Mid- latitude cirrostratus ice cloud with 0.1 g/m³ and 40 μ m mode particle radius. Note that 5 dB SNR is needed.

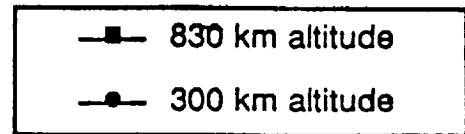
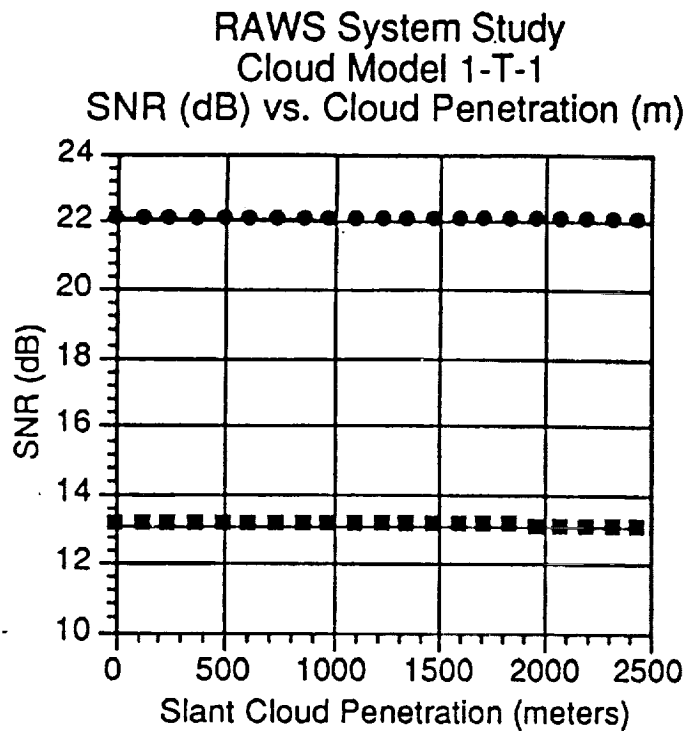


—■— SNR @ Cloud Base (dB), f=35 GHz
—●— SNR @ Cloud Base (dB), f=10 GHz

Cirrostratus, Tropical
Elevation: 6000-8000 meters
Density: 0.10 g m⁻³
Principal Component: Ice

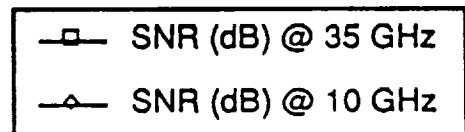
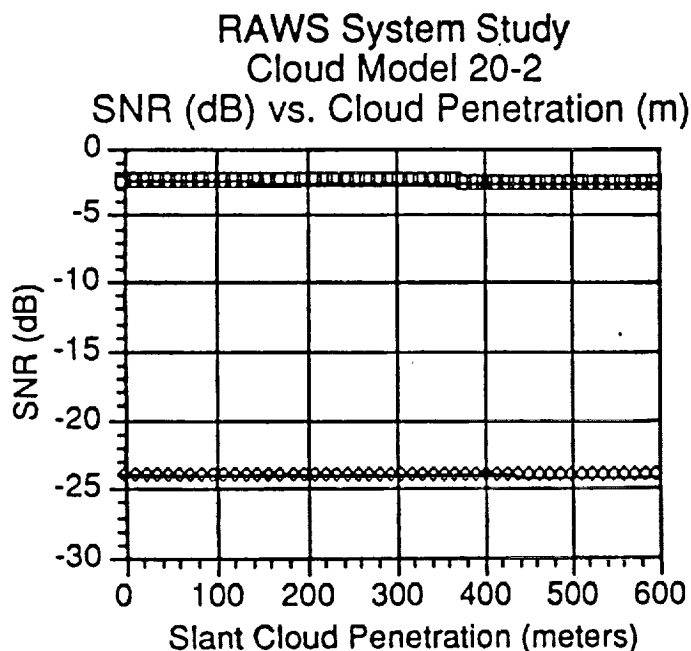
Default System Parameters

Figure 3. SNR at cloud base vs transmitter power for 800 km orbit. Tropical cirrostratus ice cloud with 0.1 g/m³ density and 40 μ m mode particle radius. Note that 5 dB SNR is needed.



Cirrostratus, Tropical
Elevation: 6000-8000 meters
Density: 0.10 g m⁻³
Principal Component: Ice

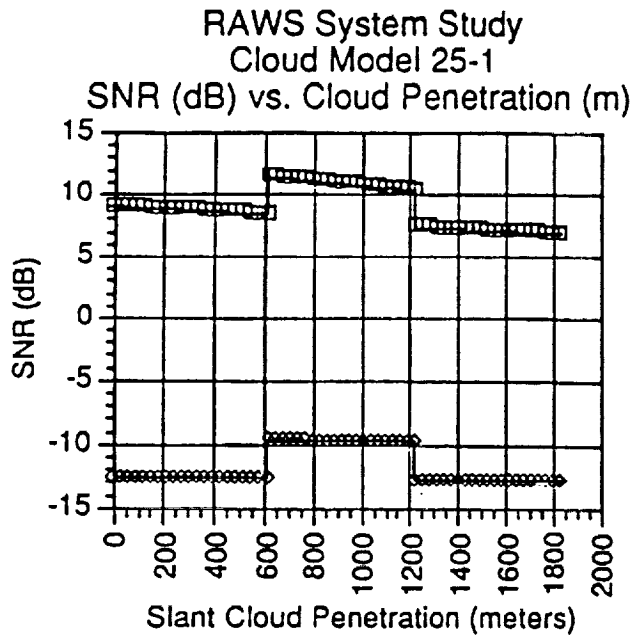
Figure 4. SNR vs cloud penetration at 35 GHz for 300 km and 800 km orbits. Tropical cirrostratus ice cloud with 0.1 g/m³ density and 40 μ m mode particle radius. Note that 5 dB SNR is needed.



Low-lying Stratus
Elevation: 500-1000 m
Density: 0.25 g m⁻³
Principal Component: Water

Default System Parameters

Figure 5. SNR vs cloud penetration for 800 km orbit. Low-lying stratus water cloud with 0.25 g/m³ and 10 μ m mode drop radius. Note that the needed 5 dB SNR is not achieved in this case.

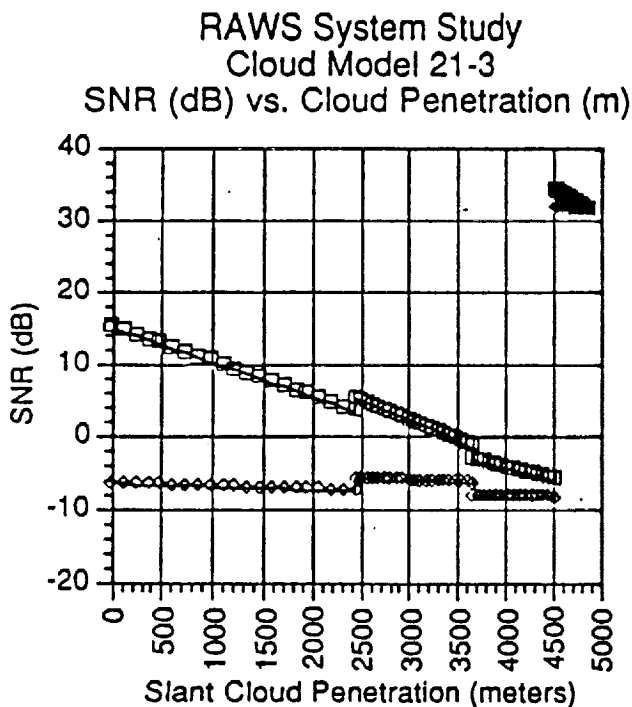


—□— SNR (dB) @ 35 GHz
—△— SNR (dB) @ 10 GHz

Fair Weather Cumulus
Elevation: 500-2000 meters
Density: 0.5 - 1.0 g m⁻³
Principal Component: Water

Default System Parameters

Figure 6. SNR vs cloud penetration for 800 km orbit. Fair weather cumulus with layers of 0.5 and 1.0 g/m³ density and 10 μ m mode drop radius. Note that 35 GHz achieves better than the required 5 dB SNR throughout, but 10 GHz does not.



—□— SNR (dB) @ 35 GHz
—△— SNR (dB) @ 10 GHz

Steady Rain, 15 mm/hr
Elevation: 0-4000 meters
Density: 1.0 -3.0 g m⁻³
Principal Components:
Water and Rain

Default System Parameters

Figure 7. SNR vs cloud and rain penetration for 800 km orbit. Rain rate is 15 mm/hr. Cloud density is 2 g/m³ above 2000 m and between 300 and 1000 m. It is 3 g/m³ between 1000 and 2000 m. Rain is below 300 m. Note that dense cloud attenuates 35 GHz to the point that it is not useful in the dense cloud for about the last 2 km of penetration. Note also that both bands have large SNRs for the rain itself.

The full results of this study will, when accompanied by suitable text, be used in consultations with meteorologists who can help establish the acceptable level for loss of data. This in turn will allow us to determine a suitable power level for RAWs.

3.3 Frequency-Measurement Study.

Xin examined many different methods used in ground-based Doppler radars to overcome the ambiguity problem associated with the requirement for a higher Nyquist sampling rate than allowable without range ambiguity. He performed Monte-Carlo simulation studies to determine the errors that would occur for different schemes with different SNRs.

The three methods on which Xin concentrated after the initial study are two staggered-PRF methods and a waveform-coding method. He showed that one of the staggered-PRF methods and the waveform-coding method are preferable, the choice depending on the width of the Doppler spectrum. To demonstrate this and other related effects, he developed a simulator and used it for extensive error studies of the different methods.

3.4 Tracking Study.

The problem of tracking the mean Doppler frequency is a significant one. Xin studied this briefly and showed how the errors depend on the nature of the phase-locked loop used in tracking. He also used simulations in this study. However, we believe that more study of this problem will be necessary.

3.5 Scanning Study.

As part of Xin's conceptual study, he examined the requirement for duration of the measurement of each radial velocity. To obtain an adequate number of independent samples, the beam would have to rotate too slowly to achieve the desired coverage. Even then, the problem might not be solved because of the forward motion of the volume of cloud caused by forward motion of the spacecraft. The conclusion is that a stepping scan is desirable. Xin showed that we can achieve this with a mechanically rotated reflector antenna by scanning the direction of the feed. The scan angle required is very small, so electronic scanning of the small feed antenna should be easy.

An electronically scanned array would also serve this purpose. Two arrays would be needed, one looking forward and one looking aft. Xin did not study the details of this arrangement. However, the beam stepping that he studied would be easy to achieve with such an antenna. Hence, it needs more study in the future.

The problem of observing the same cell in the cloud from different directions was studied cursorily. It appears that exact coincidence for the looks from different directions is not feasible with mechanical scanning. However, we believe an algorithm can be developed based on measurements from the different directions of cells near to each other. The wind-vector-scatterometer algorithms use a similar approach. Clearly this requires much more study, and it is the next major topic for our research.

4.0 CONCLUSIONS

We made significant progress on the RAWs study during the first year. Feasibility of the concept appears certain. Xin, in his dissertation, showed that the difficult problems of Doppler measurement can be solved. Further study indicates that a reasonably sized system (but not a small one) can measure with ice clouds and denser water clouds. No sensitivity problem exists for raining regions.

Although much progress occurred in this first year, the study of such a complex system at a low level of effort requires much more time. Many details must be worked out, and the application of the radar to measurement of rain rates and winds at the surface of the sea needs to be addressed.

REFERENCE

Xin, W., "A Satellite-Based Radar Wind Sensor," Radar Systems and Remote Sensing Laboratory Technical Report 8760-2, June 1991 (also University of Kansas, Lawrence, Ph.D. dissertation).